SPECIAL CIRCULAR 112 JULY 1986

# Response of Linearized Hot-Film Anemometers to Ambient Air Temperature

R.D. FOX and R.D. BRAZEE

Agricultural Research Service
U. S. Department of Agriculture
in cooperation with
The Ohio State University
Ohio Agricultural Research and Development Center
Wooster, Ohio

This page intentionally blank.

# RESPONSE OF LINEARIZED HOT-FILM ANEMOMETERS TO AMBIENT AIR TEMPERATURE

R. D. Fox and R. D. Brazee

Application Technology Research Unit
Midwest Area
Agricultural Research Service
U. S. Department of Agriculture
in cooperation with
The Ohio State University
Ohio Agricultural Research and Development Center
Wooster, Ohio

## TABLE OF CONTENTS

Response of Linearized Hot-Film Anemometers to Ambient Air Temperature


## ABSTRACT

A method was developed to adjust linearized output voltages from constant temperature hot-film sensor anemometers for operating ambient air temperatures different from calibration temperatures. This temperature compensation method was tested for 10 hot-film anemometer units at 4.2 m/s and for three hot-film anemometers at flow velocities from 0.22 m/s to 4.2 m/s; ambient temperatures were as much as 25°C less than and nine deg C greater than calibration temperature. The compensation method developed here was compared with the method of Nagib (1978); both methods corrected linearized voltages to within ten percent of calibration values for nearly all test conditions.

Response of Linearized Hot-Film Anemometers to Ambient Air Temperature

R. D. Fox and R. D. Brazee

It is well known that the response of constant-temperature hot-film (CTHF) anemometer sensors is affected by ambient air temperature. Also, CTHF sensors will likely have been calibrated at temperatures differing from ambient temperatures encountered particularly during atmospheric experiments. Atmospheric temperature may typically change 10°C during the course of a data acquisition sequence.

In the atmosphere, instantaneous wind direction changes frequently, and the three CTHF sensors required to measure the orthogonal velocity components at a location must be corrected for response of all three sensors to flow, traverse and parallel to the sensing elements. The correction can be made by means of digital or analog resolving systems based on the results of Champagne et al. (1967) (see Fox et al., 1980). However, the method of Champagne requires linear input signals, and to maintain as much accuracy as possible in the measurement-analysis system, it is desirable to include the resolving system in the anemometer calibration. Because electronic linearizers used with CTHF anemometers are matched to a particular sensor and servo-amplifier unit, this procedure requires a separate linearizer for each anemometer channel. In vegetative canopy flow studies, we routinely measure velocities at five locations simultaneously, which requires 15 anemometer channels. Thus post-experiment linearization would require an excessive delay in data processing.

The objective of this work was to develop a temperature-compensation method for a linearized CTHF anemometer system that uses cylindrical sensors.

## A TEMPERATURE-COMPENSATION THEORY

We are concerned with temperature compensation for a cylindrical CTHF sensor. The sensor can be idealized as a long thin cylinder, for which the heat lost to a normal cross-flow of air is given by King's law (Hinze, 1959) as

$$Q = I_p^2 R_p = E_p^2/R_p = [A_o + B_o U^{1/2}] (T_s - T_e) \tag{1}$$

In practice, the exponent of U, called n, (n=1/2 in Eq. 1) and the constants $A_2$ and $B_2$ that include $A_o$,$B_o$ and constants $T_s$,$T_e$, and $R_p$, are calculated from measured values $U_m$ and $E_m$ by means of the relationship

$$E_M^2 = [A_2 + B_2 U_m^n] \quad . \tag{2}$$

Two methods have been used to determine the temperature at which flow properties should be evaluated. Bearman (1971) used wire surface temperature $T_s$; Collis and Williams (1959) used film temperature, $T_F = (T_s + T_a)/2$. Bearman (1971) developed equations for correcting measured velocities for changes in ambient temperature from the calibration temperature. Bearman's (1971) method for correcting linearized hot-wire anemometer signals was based on the transfer function of the linearizer, and his results were applied primarily to ambient temperatures warmer than the calibration temperature.

Drubka et al. (1977) extended Bearman's work by developing methods for using compensating resistor circuits with a temperature-compensating hot-wire sensor in the bridge circuit of the servo-amplifier system to correct measured velocities for changes in ambient temperature. Based on Bearman's results, Nagib (1978) developed equations for nonlinear and linear temperature correction factors and tested the correction methods using several hot-wire sensors. Their equation for the linear voltage corrected for a change temperature in ambient temperature was:

$$E_L(T) \text{ corrected} = \left[ \frac{E_L^n(T) + AC^n z/B}{1 - z} \right]^{1/n} , \tag{3}$$

where

$$z = \frac{\alpha}{r-1}(T - T_0) ,$$

Technical Bulletin TB-16 (Thermo Systems, Inc., 1973) discusses temperature compensation based on the work of Collis and Williams (1959) and Freymuth (1970). The effect of environmental temperature on the non-linear voltage output from a CTHF anemometer was given by Freymuth as

$$E^2 \propto Q = \left\{ \frac{(T_s+T_e)^{0.97}(T_s-T_e)}{T_e^{0.17}} \right\} \left\{ A_1 + (T_s + T_e)^{-1.76n} B_1 U^n \right\} \tag{4}$$

The nonlinear temperature correction factor was defined as

$$F_N = U(T_c)/U(T_e) \tag{5}$$

This factor can be calculated as follows. For constant sensor temperature, $T_s$, and a specified calibration temperature $T_c$, the constants $A_1$ and $B_1$ can be calculated from Eqs. (2) and (4). Then Eq. (2) can be solved for flow velocity, $U(T_e) = U(A_o,B_o,n,E_e)$. Using anticipated ranges of values for ambient temperature and non-linear output voltages, one can generate a table of expected flow velocities $U(T_c) = U(A_1,A_2,n,E_e)$ based on Eq. (4). Then $F_N$ can be calculated from the table of velocities and Eq. (4).

A temperature correction factor for linearized CTHF signal can be derived as follows: Freymuth (1970) suggests a simple method of temperature correction by assuming the heat loss is directly proportional to the product of the temperature driving force and a function of a velocity,

$$Q = F(V)\ (T_s - T_e) \quad . \tag{6}$$

Freymuth (1970) also expressed dependence of air density on film temperature as $\rho \propto (T_s + T_e)^{-1}$ , or

$$\rho \propto T_s^{-1}[1 + (T_e/T_s)]^{-1} \quad . \tag{7}$$

Expansion of (7) with the binomial series as $\rho \propto T^{-1}[1 - T_e/T_s + (T_e/T_s)^2 - (T_e/T_s)^3 + \ldots]$ and discard of all terms beyond the linear term gives the result

$$\rho \propto T_s^{-2}(T_s - T_e) \quad . \tag{8}$$

Eqs. (6) and (8) together with the definition of $F(V) = B(\rho V)^n$ yield the expression

$$Q = B \quad V^n(T_s - T_e)^{1+n}T_s^{-2n} \quad , \tag{9}$$

or

$$Q^{1/n} = B^{1/n}(T_s - T_e)^{\frac{1+n}{n}} \quad T_s^{-2} V \quad . \tag{10}$$

For linearized anemometer, the fluid velocity is related to the output signal as $V = CE_L$, and because the linearized signal is always adjusted to zero under prevailing conditions,

$$Q^{1/n} = E_L \tag{11}$$

For calibration at $T_e = T_c$, Eq. (10) yields

$$V = CE_c = B^{-1/n} (T_s - T_c)^{-\frac{1+n}{n}} T_s^2 E_c \quad . \tag{12}$$

The temperature-correction factor, F, must satisfy the relationship

$$V = F \cdot CE_e \quad . \tag{13}$$

For constant velocity V, we have $V = CE_e = C_e E_e$ and $F = V/CE_e = C_e/C$. Using Eq. (10), we then find

$$F_L = \left( \frac{T_s - T_c}{T_s - T_e} \right)^{\frac{1+n}{n}} \quad . \tag{14}$$

Two-temperature correction factors have been discussed so far, a third will be discussed later. The non-linear correction factor $F_N$, was calculated using Eq. (5). However, the values in Eq. (5) are calculated from Eqs. (2) and (4). The linear correction factor, $F_L$, is calculated from Eq. (14). The measured temperature correction factor, $F_M$, is calculated from hot-film anemometer output signal voltages at the calibration temperature and output voltages at the experimental temperatures. Both $F_M$ and $F_L$ are compared to the measured factor $F_M$ in the results section.

## Experimental System

The experimental system used to test the temperature compensation theory is shown in Fig. 1. Cold, outside air was used to attain and hold the low temperature of -7°C while an electric heater was used to obtain the high temperature of 29°C. Temperatures between these extremes were obtained by blending outside air and room air through a mixing chamber into a small calibration wind tunnel.

The CTHF systems used were the Flow Corporation(FC) Model 700-4 and the Thermo-Systems, Inc. (TSI)* Model 1054B. A TSI Model 1054A was used as a calibrated standard with a TSI Model 1210-60 probe having a single sensor. The CTHF sensors used were component sensors of TSI Model 1294 3-dimensional probes. The 60-series sensors are 152 μm in diameter and have a sensing length of 2 mm. The model 1294 probe has three orthogonal sensors arranged as intersecting edges of a cube, with each sensor mounted at an angle of 54.8° with respect to the longitudinal axis of the probe. A digital printer sequentially recorded totalized one-second average values of the mean output signal, the RMS signal value, and the tunnel air temperature.

## Procedure

Initial adjustment of the CTHF anemometer systems was performed at an ambient air temperature of 21.1°C. The sensor operating temperature and linearized zero output were set with the sensor retracted into a probe guard. The linearized gain was adjusted with the sensor in a vertical plane, normal to flow, in the center of the tunnel, such that a 10 volt signal was produced for a flow of 6.1 m/sec.

For each sensor, the non-linear output voltage was measured for an air velocity of 0 to 4.5 m/s, at an air temperature of 21.1°C. An iterative least squares procedure was used to obtain the coefficients, $A_o$, $B_o$, and n, which gave the best fit to the measured values of $E_m$ and $U_m$ according to the relationship given in Eq. (2). For constant air flow rates through the wind

*Mention of a trademark of a proprietary product does not consitute a guarantee or warranty of the product by the U. S. Department of Agriculture, and does not imply its approval to the exclusion of other products that may also be suitable.

tunnel, voltage signals from CTHF anemometers were recorded at approximately 3°C increments over an ambient air temperature range of 29°C to -7°C. The mean of five, one-second average values was recorded. For each experiment, the linearized voltage measured at each temperature was corrected to calibration-temperature equivalent voltages by using Eq. (3) and Eq. (14). The two methods of temperature compensation were compared.

Effect of Air Velocity

Fig. 2 displays anemometer linearized output voltage for a range of ambient temperatures. At velocities near 4.2 m/s, the dimensionless voltage change for a given change in ambient temperature is close to values reported by Nagib (1978). However, at lower velocities, the change in linearized voltages with a change in ambient temperature appears to be a function of air velocity. While Nagib (1978) did not observe this velocity effect, Eq. (4), his temperature adjustment equation, includes uncorrected linearized voltage as a factor.

Eq. (14) is not a function of velocity, and as such will not correct low-velocity temperature effects as displayed in Fig. 2. Consider an empirical velocity exponent m, where

$$F_L = \left(\frac{T_s-T_c}{T_s-T_e}\right)^{\frac{1+m}{m}} \tag{15}$$

The effect of flow rate on $F_L$ as expressed by the m-value, m=g(U), is displayed in Fig. 3 for measured n-values and for m-values calculated from non-linear calibration data using Eq. (4). The empirical function, m=g(U), was found by calculating the expected non-linear factor $F_L$, and then substituting the resulting value of $F_N$ and $F_L$ in Eq. (15), which had been solved for m. These m-values were averaged for a range of ambient temperatures to calculate the mean m value for a given velocity. This was repeated for several velocities and the results plotted in Fig. 3. For sensors 5113-1 and 5113-3, the empirical relationship is

$$m = C_o n \left\{U(T_c)\right\}^{C_1} \tag{16}$$

where $C_o = 0.58$ and $C_1 = 0.38$. By this method, one measures $U(T_e)$ and $T_e$, uses $U(T_e)$ as an estimate for $U(T_c)$ to calculate m from Eq. (16); $F_L$ is calculated from Eq. 15.

Comparison of Correction Methods

In addition to measured values, Fig. 2 displays linearized anemometer output voltages as adjusted for ambient temperature by both Eq. (3) and by Eqs. (16) and (15). For these two sensors and associated servo-amplifiers, both temperature adjustment methods are equally effective; maximum error at temperatures 25°C below calibration temperature was below 5% in all but two instances. In Fig. 4, we have plotted measured, linearized voltages and adjusted voltages for seven different CTHF anemometer units, at a flow rate of 4.2 m/s. Again, both Eq. (3) and Eqs. (16) and (15) effectively adjust linearized voltages for ambient temperature changes.

## Conclusions

At air velocities below 4 m/s, the correction required to compensate linearized CTHF anemometer voltage signals for changes in ambient temperature is a function of air flow velocity. The equations developed in this study correct linearized CTHF anemometer voltages to within ten percent of calibration values for ambient air temperatures as much as 25°C less than and 9°C greater than calibration temperature. The temperature compensation method developed in this study is about as effective as the method of Nagib (1978) in compensating linearized CTHF anemometer voltages for changes in ambient air temperatures.

We can list procedures for calibration and use of CTHF sensor at temperatures near freezing from most desirable to least desirable:

1. Calibrate at experimental temperature;
2. Use temperature compensated sensors;
3. Use non-linear signals, temperature compensate then linearize;
4. Use a linear signal correction method such as we developed here or the method of Nagib (1978).

Bibliography


(1) __________. 1973. Temperature Compensation of Thermal Sensors. Technical Bulletin TB-16, Thermo-Systems, Inc. St. Paul, MN. 6 pp.

(2) Bearman, P. W. 1971. Corrections for the effect of ambient temperature drift on hot-wire measurements in incompressible flow. DISA Information No. 11, pp. 25-30.

(3) Champagne, F. N., C. A. Sleicher, and O. H. Wehrmann. 1967. Turbulence measurements with inclined wires. Journal of Fluid Mechanics 28:153-175.

(4) Collis, D. C., and M. J.Williams. 1959. Two-dimensional convection from heated wires at low Reynolds numbers. Journal of Fluid Mechanics 6:357-384.

(5) Drubka, R. E., J. Tan-atichat, and H. M. Nagib. 1977. Analysis of temperature compensating circuits for hot-wires and hot-films. DISA Information No. 22, Dec. pp 5-14.

(6) Fox, R. D., R. D. Brazee, W. R. Alvey, W. R. Boyes, and A. W. Swank. 1980. A data management system for studying wind profiles in orchard and field crops. Transactions of ASAE 23(4):978-984.

(7) Freymuth, P. 1970. Hot-wire anemometer thermal calibration errors. Instruments Control Systems, October, pp. 82,83.

(8) Hinze, J. O. 1959. Turbulence. McGraw-Hill Book Company, Inc., New York. 586 pp.

(9) Nagib, H. M. 1978. Personal communications.

## Symbols Used

| | |
|---|---|
| $A_0, B_0$ | Constants in King's law. |
| $A_1, B_1$ | Constants in Freymuth's temperature-response equation. |
| C | Slope of linear voltage/velocity regression. |
| E | Signal output voltage from CTHF anemometer. |
| F | Factor to correct CTHF output voltage for ambient temperature |
| I | Current through CTHF sensor. |
| m | Constant in linear temperature-correction factor equation. |
| n | Constant in nonlinear CTHF flow response equation (modified King's law). |
| Q | Heat loss from sensor |
| r | Overheat ratio. |
| R | Resistance of CTHF sensor. |
| $T_s$ | CTHF sensor operating temperature $^oK$. |
| $T_e$ | Environmental temperature, $^oK$. |
| $T_c$ | Ambient temperature during CTHF sensor calibration, $^oK$. |
| U | Air velocity, m/s. |
| $\rho$ | Density of air, $kg/m^3$. |
| $\alpha$ | Temperature coefficient of hot-film sensor. |

## Subscripts Used

| | |
|---|---|
| c | Subscript referring to sensor operation during calibration. |
| e | Subscript referring to sensor operation during any environmental condition. |
| L | Subscript referring to linear. |
| M | Subscript referring to measured. |
| N | Subscript referring to non-linear. |
| s | Subscript referring to hot-film sensor. |

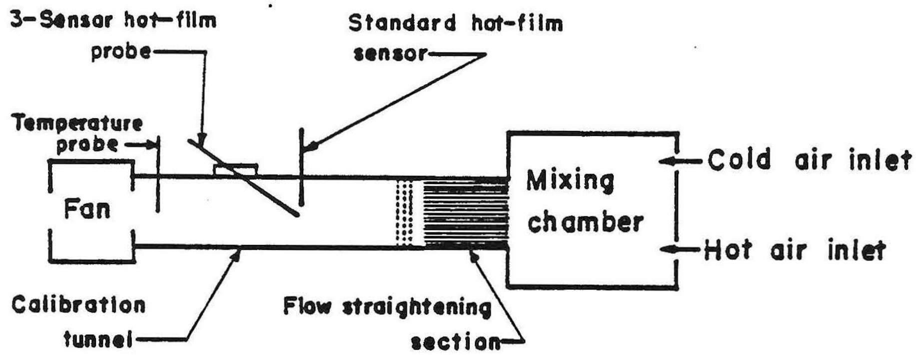


Fig. 1. System to control temperature and air flow.

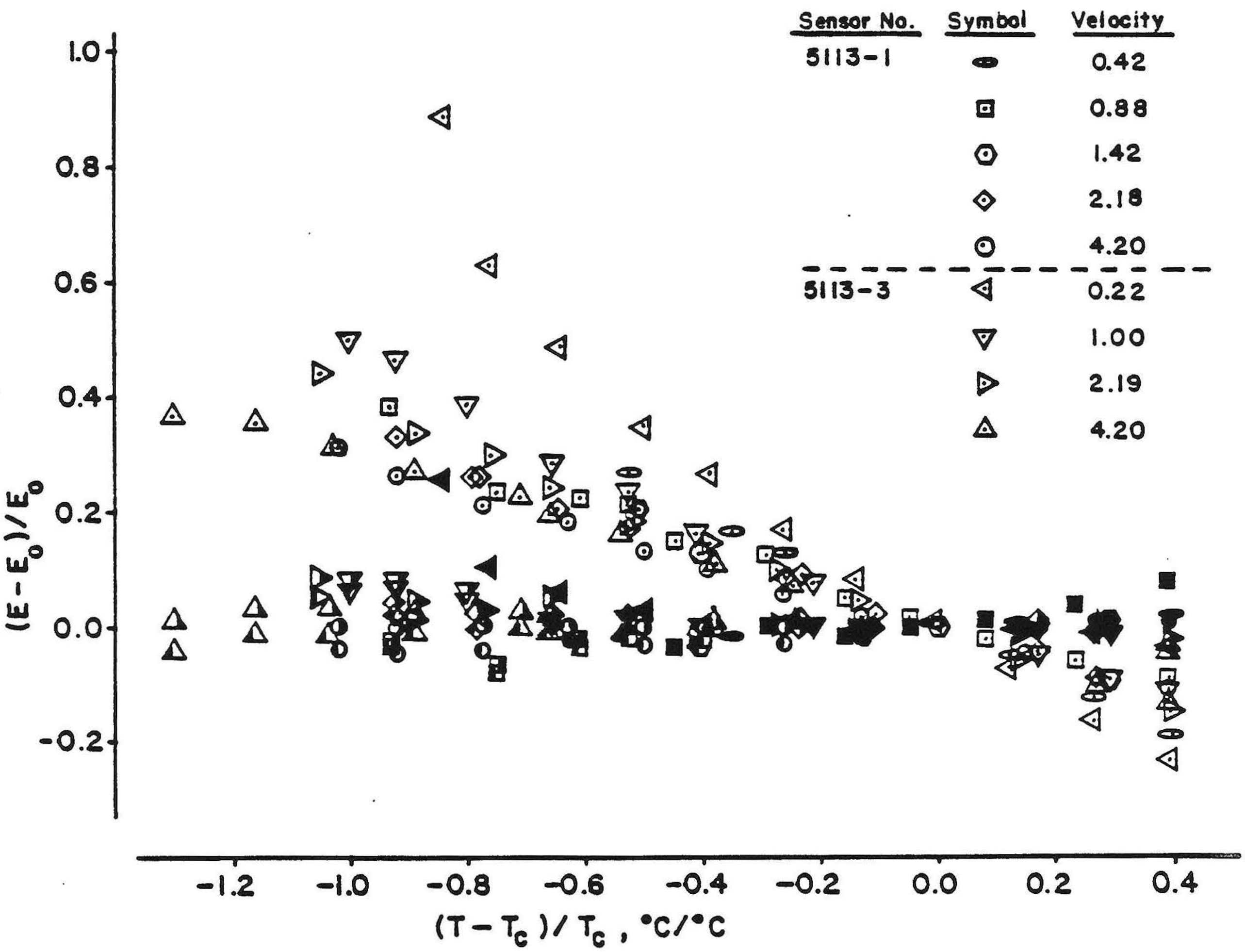


Fig. 2. Effect of changes in ambient temperature on linearized output voltages for contant-temperature hot-film anemometers; a comparison of the effectiveness of temperature compensation methods over a range of air velocities. Open symbols are measured values; shaded symbols are corrected values according to: (1) Nagib (1978) (Eq. 3), left-half shaded; (2) method of this study (Eqs. 15 and 16), right-half shaded.

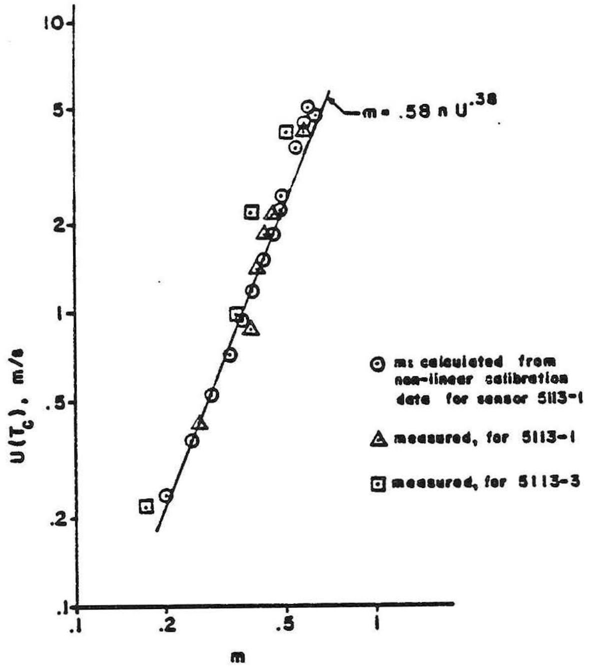


Fig. 3. Relationship between linear temperature correction constant, m, and air flow velocity over the sensor.

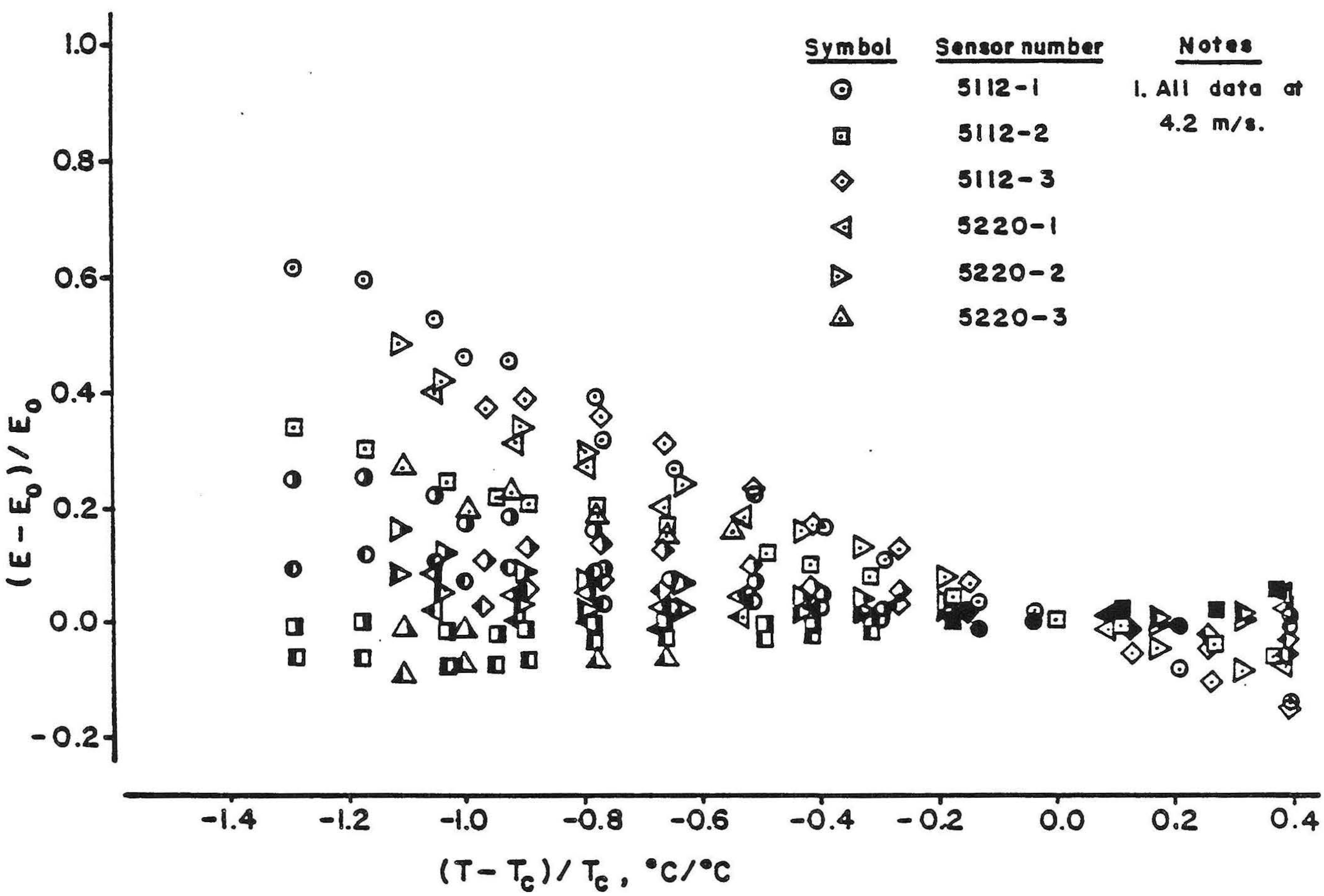


Fig. 4. Effect of changes in ambient temperature on linearized output voltages for constant-temperature, hot-film anemometers; a comparison of the effectiveness of temperature compensation methods for 4.2 m/s air velocity. Symbols are defined in Fig. 2.

This page intentionally blank.

The Ohio State University
Ohio Agricultural Research and Development Center